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An Investigation of the Physical Properties of Erupting Solar Prominences

Richard C. Altrock

Air Force Research Laboratory
National Solar Observatory
Sunspot, NM 88349

Roberto Casini

High Altitude Observatory
P. O. Box 3000
Boulder, CO 80307

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AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
29 Randolph Road
AIR FORCE MATERIEL COMMAND
Hanscom AFB, MA 01731-3010

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This technical report has been reviewed and is approved for publication.

/signed/
Robert A Morris, Chief
Battlespace Environment Division

/signed/
Richard Altrock
Research Physicist

/signed/
Dwight T. Decker, Chief
Space Weather Center of Excellence

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Air Force Research Laboratory /AFOSR/RSE
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14. ABSTRACT

The goal of this task was to determine the spectro-polarimetric properties of solar prominences leading to their activation and/or eruption into the interplanetary medium as coronal mass ejections (CMEs). This is accomplished by measuring the velocity and three-dimensional magnetic field of prominences using a new instrument, the Prominence Magnetometer (ProMag). Supporting observations of the corona overlying the prominences are obtained with an existing coronal photometer and incorporated into the analysis. This unique database will be used to study the structure and evolution of prominences, including their intimate interaction with the magnetic fields responsible for their support in the solar corona, until such time as they may erupt. The anticipated future result is the ability to predict the eruption of individual prominences and the following CMEs from the observable characteristics of the prominences. We have accomplished the successful construction, installation at the proposed research site, verification of the design concept and initial observations.

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1. SUMMARY

The goal of this task was to determine the spectro-polarimetric properties of solar prominences leading to their activation and/or eruption into the interplanetary medium as coronal mass ejections (CMEs). This is accomplished by measuring the velocity and three-dimensional magnetic field of prominences using a new instrument, the Prominence Magnetometer (ProMag). Supporting observations of the corona overlying the prominences are obtained with an existing coronal photometer and incorporated into the analysis. This unique database will be used to study the structure and evolution of prominences, including their intimate interaction with the magnetic fields responsible for their support in the solar corona, until such time as they may erupt. The anticipated future result is the ability to predict the eruption of individual prominences and the following CMEs from the observable characteristics of the prominences. The impact of CMEs on geospace often produces severe space weather effects on Air Force systems. We have accomplished the successful construction, installation at the proposed research site, verification of the design concept and initial observations.

2. INTRODUCTION

Solar prominences are aggregations of material in the solar corona of much higher density and much lower temperature than the corona. They are intimately connected with magnetic fields in the corona, which are rooted in the photosphere. The term prominence is traditionally used for these features when observed above the limb and filament when observed against the disk. We will use the term prominence in both cases. Figure 1 demonstrates a prominence observed by the Solar and Heliospheric Observatory (SOHO) (ESA & NASA).

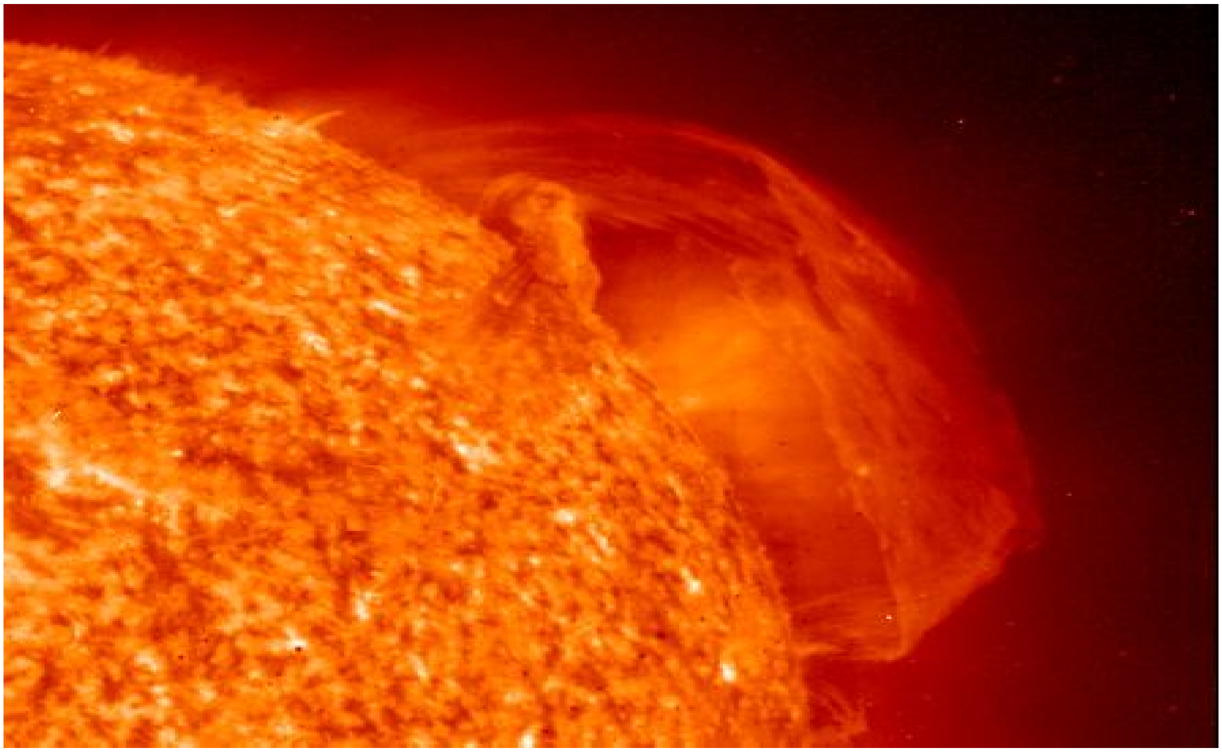

Figure 1: A Prominence Observed by the SOHO Extreme Ultraviolet Imaging Telescope (EIT)

The properties of prominences have been debated for decades. At the current time, there is no agreement concerning their creation, how they are supported in the corona, magnetic fields, velocity fields, evolution and ultimate disappearance. This task attempted to provide answers to these questions through study of prominences using a new instrument, the Prominence Magnetometer (ProMag). This instrument was designed and constructed by the High Altitude Observatory (HAO) and installed in the John W. Evans Solar Facility (ESF) of the Sacramento Peak site of the National Solar Observatory (NSO) in Sunspot, NM. Elmore et al. (2008) describe an early version of ProMag. The HAO Principal Investigator (PI) is Dr. Roberto Casini. This facility was selected due to the availability of the ESF 40-cm coronagraph as a light feed. This coronagraph provides observation of material above the limb with very high precision, due to its property of very low scatter of incident light within the telescope. For example, internal scattering is approximately 1000 times less than in the NSO Dunn Solar Telescope. Figure 2 shows the ESF.

Figure 2: The John W. Evans Solar Facility of the Sacramento Peak Site of the National Solar Observatory

The ultimate objective of this study is to determine the observable properties of prominences that lead to their activation and/or eruption into the interplanetary medium. The ability to be able to predict when this occurs will lead to a major increase in the ability to predict the onset of Coronal Mass Ejections (CMEs), which are associated with eruptive or active prominences 90% of the time (de Toma and Casini, 2006). Prediction of CMEs is a major goal of the Air Force Weather Agency, since CMEs impacting the Earth cause major Space Weather effects.

A Memorandum of Understanding between the Association of Universities for Research in Astronomy (which operates NSO) and the University Corporation for Atmospheric Research (which operates HAO) provides for installation of the ProMag in the ESF and its operation.

AFRL/RVBXS participated in the analysis of data from ProMag by providing contextual observations of the corona in the lines Fe X 637.4 nm, Fe XIV 530.3 nm and Ca XV 569.4 nm obtained with the ESF Coronal Photometer. The contextual observations aid in the identification of the brightest regions in the corona above prominences, which can be used to identify the best targets. The contextual Fe X and Fe XIV data can also be used

to estimate coronal temperatures above prominences outside of active regions for comparison with ProMag results.

3. INSTRUMENTATION

The Prominence Magnetometer (ProMag) is a spectro-polarimeter deployed at the ESF. It is mainly conceived to do spectro-polarimetry of the chromosphere (in particular prominences and filaments) simultaneously in the He I lines at 587.6 nm (D3) and 1083.0 nm (off-limb mode), or in H-alpha 656.3 nm and 1083.0 nm (on-disk mode). However, it can also be used to observe the corona in the forbidden emission lines of Fe XIII at 1 micron. ProMag is designed to achieve a spatial resolution of better than 3 arcsec and a spectral resolution of 50 mǺ, at 587.6 nm.

The instrument consists of a dual-beam polarimeter (modulator + analyzer) placed at the prime focus (F1) of the ESF 40-cm coronagraph (shown in Figure 3), and a grating-based spectrograph placed on the East (optical) Bench in the separate climate-controlled observing room of the ESF. The polarimeter consists of a Ferroelectric-Liquid-Crystal-based polychromatic modulator (implementing two FLCs and a fixed waveplate) that allows for efficient modulation (better than 40%) over a spectral range encompassing the solar lines listed above. A Wollaston-based beam-splitter is adopted as analyzer. The spectrograph consists of an image rotator, a slit assembly, a dispersion grating, and two camera packages, one for the visible and one for the near-IR (infrared). The function of the image rotator is to keep the beam-splitting direction (typically aligned with the solar radius) of the two beams from the polarimeter always aligned with the slit. The polarimeter can also be rotated to align the slit to any given direction on the solar disk. The mapping of a solar structure is performed by stepping the slit across the image plane.

The spectrograph has one visible and one IR channel. The order selection of the grating was optimized for the simultaneous observation of the two He I lines. However H-alpha and He I 1083.0 nm can also be observed simultaneously, with only minor vignetting. The detectors are a 652x496 pixel Pluto camera for the visible range, and a 320x256 pixel FLIR alpha-NIR camera for the IR.

Figure 3: ProMag Mounted at the Prime Focus of the ESF 40-cm Coronagraph

The output can be converted to two-dimensional maps of vector magnetic fields, line-of- sight velocities, temperature, optical depth and density in prominences, similar to Figure 4, which is taken from a different instrument. The data will be reduced by HAO and made publicly available. HAO has already developed suitable codes for analyzing spectro-polarimetric data that utilize principal component analysis and sophisticated techniques for including the Hanle effect and atomic orientation. For further information on ProMag, go to http://www.csac.hao.ucar.edu/csac/prototypes.jsp

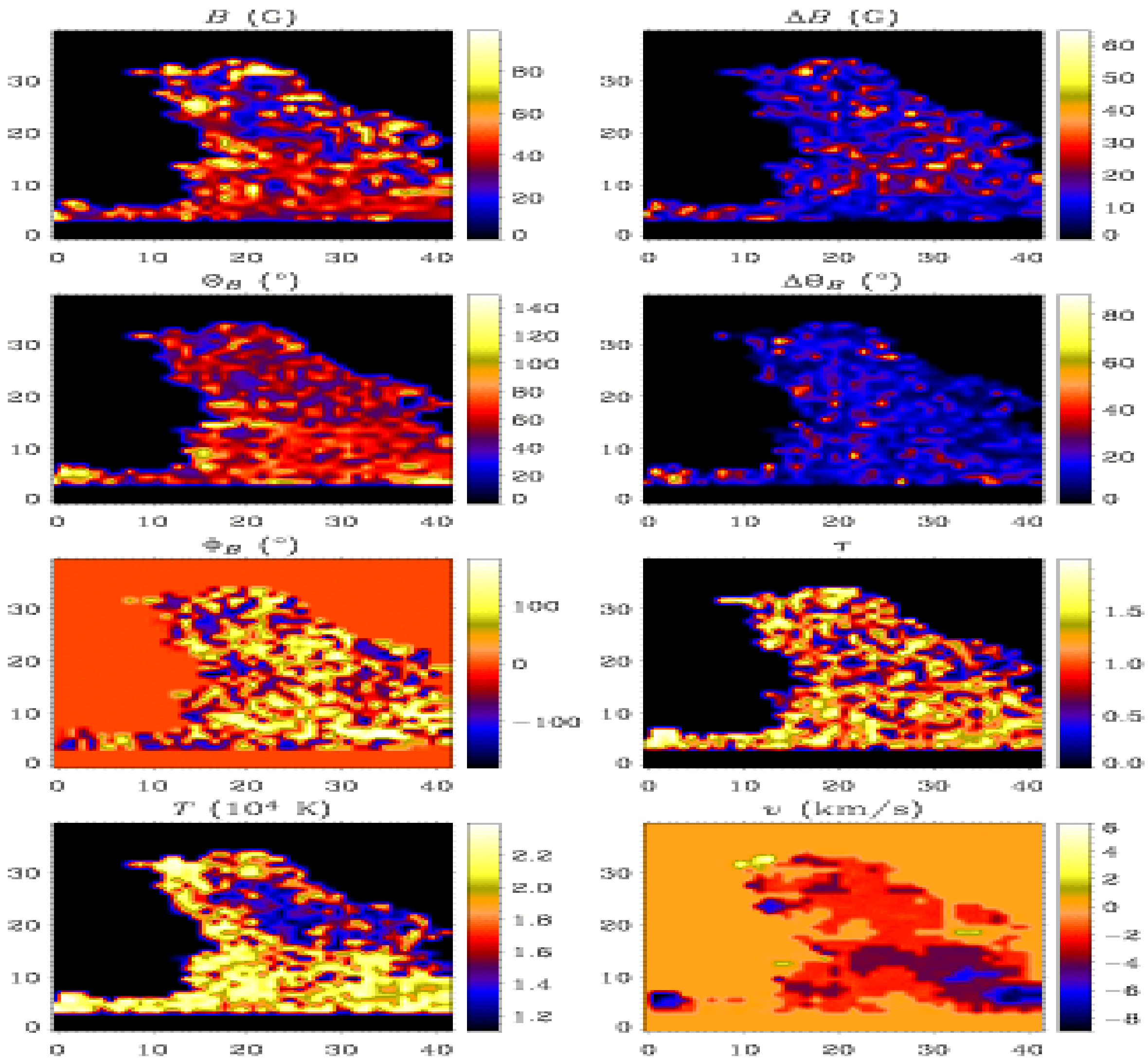

Figure 4: Magnetic Map of a Quiescent Prominence Observed in May 2002 with The Advanced Stokes Polarimeter at the NSO Dunn Solar Telescope, Obtained by Inverting Spectro-Polarimetric Data in He I D3; x and y Axes are Expressed in Pixel Units (for a 2 Arcsec Pixel); Field Geometry (Θ, Φ) is Given in the Reference Frame of the Line-Of-Sight; τ, T and v are, Respectively, the Inferred Optical Depth, Temperature, and Velocity of the Plasma Along The Line-Of-Sight; Note the Presence of Fields of the Order of 100 Gauss in Localized Regions of the Prominence Plasma, Significantly Above the Average Magnetic Field of ~20 Gauss that is Typical of These Structures; Θ is the Inclination of the Magnetic Field B on the Line-Of-Sight; Φ is the Position Angle of the Magnetic Field Projection on the Plane of the Sky; Δ = 90% Error

4. RESULTS

Weather and instrumental problems resulted in not completing the intended observations and analysis. The polarimeter and attendant mechanisms (including the spectrograph) were installed at the ESF in Mar 2008. Tests indicated a problem with characterization of the FLCs that produce the polarization. The FLCs were removed and returned to HAO for recharacterization. In fact, the polarization modulator was completely redesigned and thoroughly tested in the laboratory in the first half of 2009. In the interim we identified several parts of the ProMag occulting plate that possibly needed correction, and we improved the scattered light characteristics of the occulter and the 40-cm coronagraph. ProMag was finally successfully deployed in August 2009. Preliminary calibration data taken during the deployment run have confirmed the high modulation efficiencies attained by the polarimeter, which are very close to those predicted by the design. The first official observing run with ProMag was scheduled for Oct 2009, but due to bad weather was successful only in verifying the proper operation of the unit.

In Mar 2010 the ProMag team returned to NSO for another observing run. After completing one set of scans, the HAO PI became suspicious of a problem and examined the polarimeter. He determined that one of the components was damaged, although he could not determine the nature of the damage without disassembling the polarimeter. As a consequence, he removed the polarimeter from the coronagraph and took it back to HAO for analysis. He found that a crack had occurred in one of the wedges of the first Wollaston prism of the polarizing beam-splitter. He determined that the cause was a flawed design of the Wollaston prisms obtained from a contractor, who had cemented the two wedges together, instead of joining them with optical oil to allow for expansion/contraction caused by temperature variations.

After repairing and testing the polarimeter, the team returned to NSO in Aug 2010. The polarimeter was reinstalled in the spar at the ESF. A guiding problem delayed observations for several days but was finally diagnosed by NSO technicians. A "work-around" allowed observations to begin, and a data set was obtained on 26 Aug. The ProMag team returned to Boulder on 27 Aug to begin data reduction and analysis. They found that the flux budget was not sufficient to reach the expected polarimetric sensitivity in He I 587.6 nm (D3), although the observations in He I 1083.0 nm were satisfactory. Plans for future observations are to increase the number of data acquisitions in D3 to improve the signal-to-noise ratio. A new AFOSR task has been approved to continue the observations.

Figure 5 displays the ProMag He I 1083.0 nm image of the prominence observed in Aug 2010.

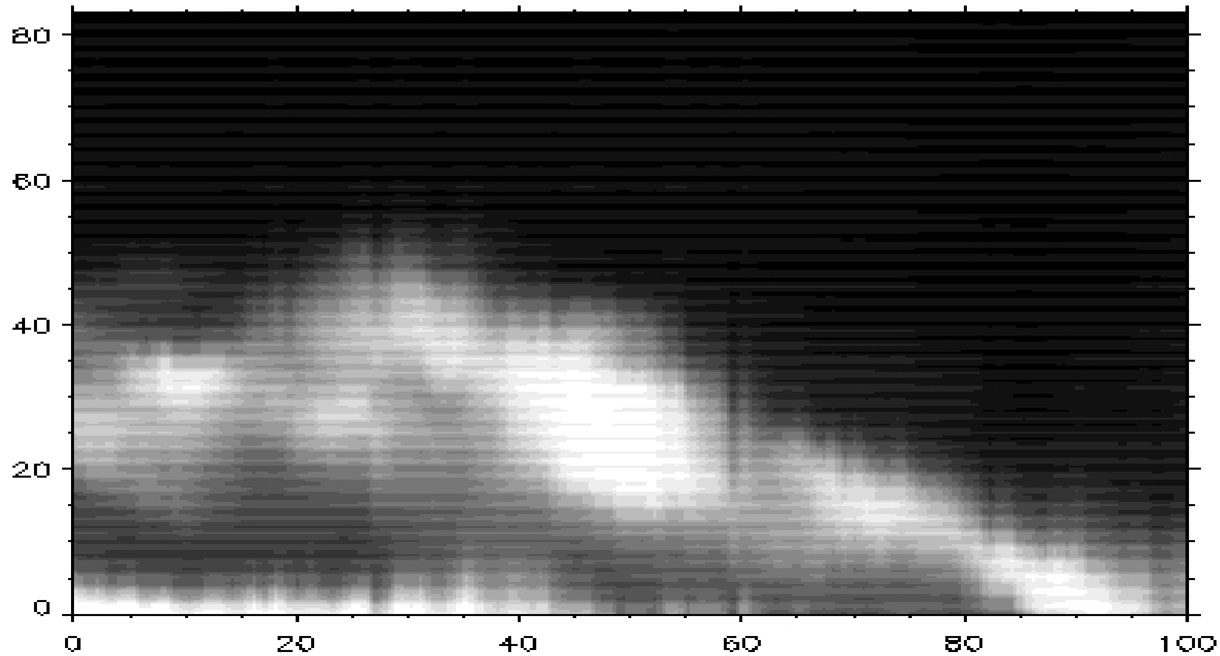

Figure 5: Image of a Prominence (off-limb) in He I 1083.0 nm Obtained in Aug 2010 with ProMag

Figure 6 displays the four Stokes polarization parameters (http://en.wikipedia.org/wiki/Stokes_parameters) in He I 1083.0 nm obtained by ProMag for the prominence shown in Figure 5. Note the dominant negative Q, which is in theoretical agreement with the fact that the +Q direction (which coincides with the beam-splitting direction) was perpendicular to the limb. Instrumental polarization is undetectable to better than 10^{-3}. The Q profile indicates a dominant, limb-tangent scattering polarization in the red component. The near-to-zero Q signal in the blue component indicates that the prominence was optically thin in 1083.0 nm.

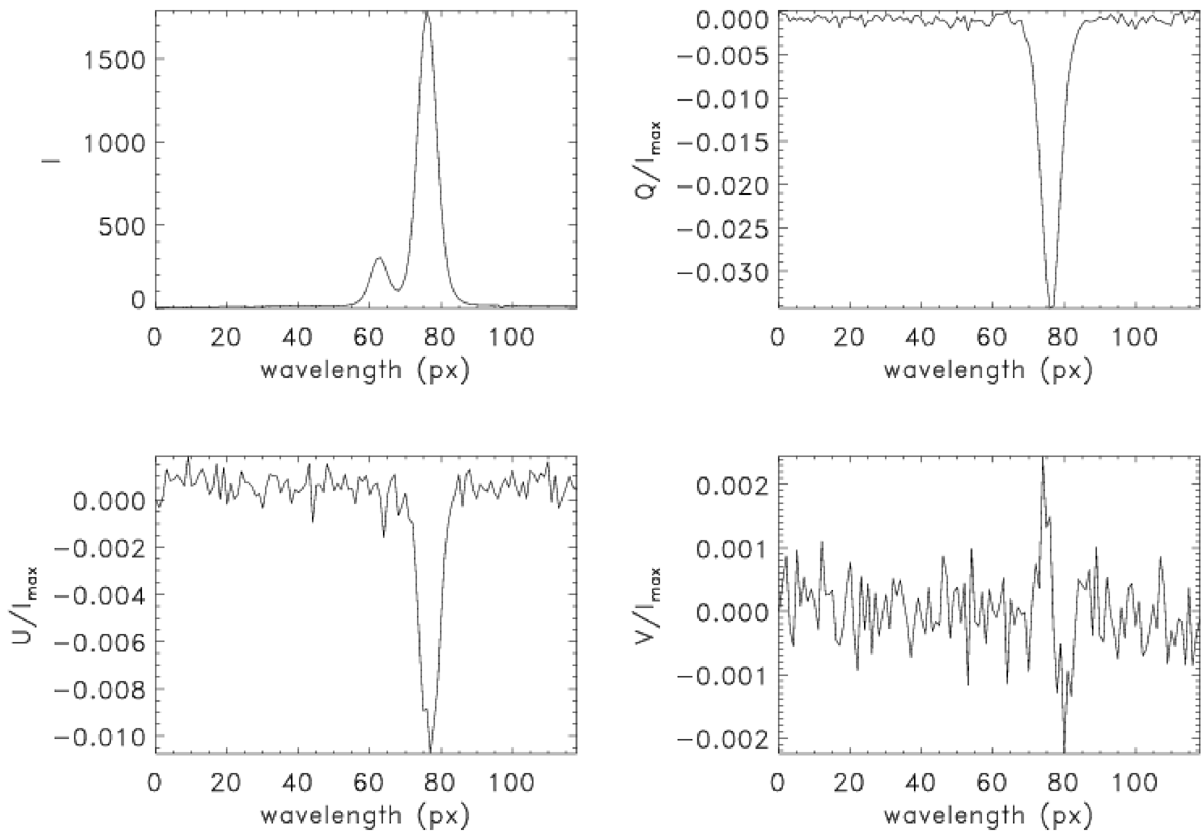

Figure 6: He I 1083.0 nm Stokes Magnetic Field Parameters I, Q, U and V (Left to Right, Top to Bottom) for the Prominence Shown in Figure 5; Data Points are Ordered in Wavelength

5. CONCLUSIONS

This task has made substantial progress towards the goal of observing prominences and analyzing their physical processes. The follow-on task soon to be initiated should allow sufficient numbers to be observed to understand the destabilizing forces that result in CMEs.

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